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Analysis method for Thomson scattering diagnostics in GAMMA 10/PDX

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We have developed an analysis method to improve the accuracies of electron temperature measurement by employing a fitting technique for the raw Thomson scattering (TS) signals. Least square fitting of the raw TS signals enabled reduction of the error in the electron temperature measurement. We applied the analysis method to a multi-pass (MP) TS system. Because the interval between the MPTS signals is very short, it is difficult to separately analyze each Thomson scattering signal intensity by using the raw signals. We used the fitting method to obtain the original TS scattering signals from the measured raw MPTS signals to obtain the electron temperatures in each pass. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4963161]

I. INTRODUCTION

Thomson scattering (TS) diagnostics is one of the most useful methods for measuring electron temperature, T_e, and density, n_e, in fusion plasmas.[1–14] For the tandem mirror GAMMA 10/PDX, we developed TS diagnostics for T_e and n_e measurements for single laser and plasma shots.[6] The value of n_e ($\sim 2 \times 10^{18}$ m^{-3}) in the GAMMA 10/PDX plasma is typically lower than that in other fusion plasmas.[15] The TS signal processing method is important when the TS signal is weak. We therefore adopted a large solid angle of TS collection optics and high-sensitivity detection systems for the weak TS signals. In a polychromator-type TS system in fusion devices, a high-speed charge-to-digital converter system is usually used to obtain the TS signal intensity.[1,2,4] Some TS systems use high-speed analog-to-digital converters or oscilloscopes to obtain the raw signal waveforms.[6–11] The output signals of the polychromators in a TS system are normally fitted to a Gaussian function in order to obtain the single-pass TS signal intensities.[7–11] TS data processing methods for raw TS signals with high-time-resolution data acquisition systems have been developed for electron temperature and density measurements, e.g., Monte-Carlo simulation for analyzing TS signals,[12] maximum-likelihood fitting method for TS fitting data,[13] and non-Gaussian pulse shape fitting method.[14] Since most of these methods are complex, we used a simple pulse shape fitting method that considers the decay time of the output signal of the polychromator in the TS system. At the plasma edge region, the TS signal intensity is very low, and the signal-to-noise ratio is low, i.e., ~3. The TS system in GAMMA 10/PDX can measure the radial profiles of T_e and n_e at six radial positions of X = 0, ±5, ±10, and −15 cm. The errors in the measured T_e and n_e are normally about 30% and 50%, respectively, when using the normal analysis method that involves summing the signal intensity without performing the fitting. To increase the TS signal intensity, multi-pass (MP) TS systems have been developed in some fusion devices.[3,16,17] We have previously developed an MPTS system with polarization control and image relaying optical systems.[18]

In this study, we developed a TS analysis method with a fitting technique to reduce the error in the electron temperature measurement for raw TS signals. The MPTS system enables high-time-resolution measurements of the electron temperature with calculation of the electron temperature in every pass. Such high-time-resolution TS measurements are required in high-frequency fluctuation plasma experiments, such as Alfvén ion cyclotron (AIC) modes, electron cyclotron heating experiments, and pellet injection experiments.

II. ELECTRON TEMPERATURE ANALYSIS METHOD

The GAMMA 10/PDX-TS system consists of a YAG laser (2 J/pulse, pulse width of 10 ns, and repetition rate of 10 Hz), large solid angle TS collection optics, and filter-type polychromators. The output signals of the polychromators are lead to high-speed digital oscilloscopes (IWATSU DS5524, 1 GSa/s, 200 MHz). The polychromators consist of the five wavelength interference filters and five silicon avalanche photodiodes (APDs) with preamplifiers. The preamplifier can amplify the input signals 20 times with a high-speed operational amplifier. Figure 1 shows the wavelength sensitivity of the polychromator and the normalized TS spectrum at T_e = 30 eV.

In the previous analysis method, the TS signal intensities were obtained by integrating the raw TS signals measured by the oscilloscopes during 75 ns. This method is not suitable

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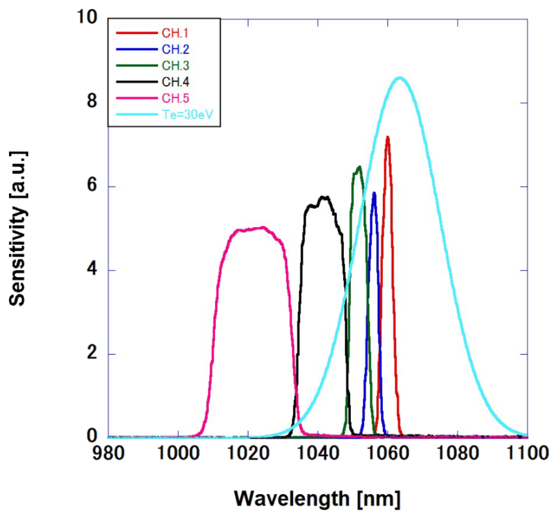

FIG. 1. Wavelength sensitivity of the polychromator and normalized TS spectrum at $T_e = 30$ eV.

for the multi-pass TS signal analysis because the multi-pass TS signals are quite close to each other.

First, we fitted the measured Raman scattering signal that had no background electromagnetic noise and stray light. Setting this signal as the base scattering signal waveform of the output signal of the polychromator is advantageous. Figure 2 shows the measured Raman signal (red solid line) and the fitted waveform (blue dotted line) fitted using the following fitting function. The waveform function f is shown by the discrete convolution of the impulse response g and the scattering signal h,

$$f(t) = \sum_{\tau=0} g(\tau)h(t-\tau), \tag{1}$$

$$g(t,\tau') = e^{t/\tau'}, \tag{2}$$

$$h(t, \mathrm{A}, t') = \mathrm{A} \cdot \exp\left(-\frac{(t-t')^2}{d}\right). \tag{3}$$

Here, τ is a variable, τ' is the time constant of the RC circuit at approximately 20 ns, A is the signal intensity, and t' is the start time of the scattering signal. The pulse width d of

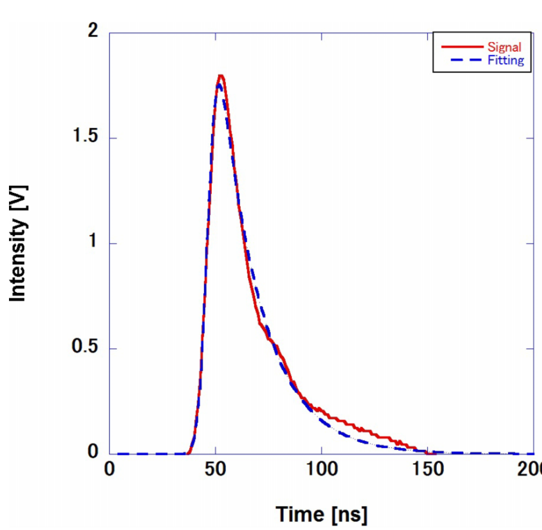

FIG. 2. Fitted waveform and measured Raman signal.

scattering signal h is 25 at approximately 10 ns. We use τ', A, and t' as the parameters. The correlation coefficient is 99%.

The chi-square method is used for measuring the electron temperature and error with the signal intensities, background noises, and a lookup table that contains the calculated intensities expected in each channel up to 200 eV at 1 eV intervals. In the conventional method, the signal intensities are analyzed by using the previous analysis method. The measurement accuracies are 34 ± 4 eV at X = 0 cm and 27 ± 8 eV at X = 10 cm with the average of over 70 plasma shots. The error ratios are 13% and 30% at X = 0 cm and X = 10 cm, respectively.

Through analysis using the new fitting method, we can obtain the integrated signal intensities from the waveform function f. The obtained electron temperatures at X = 0 cm and X = 10 cm are 37 ± 4 eV and 27 ± 6 eV, respectively. The chi-square values decrease, and the measurement accuracies are improved from 13% to 11% at X = 0 cm and 30% to 22% at X = 10 cm in terms of the error ratio. This analysis method has a large effect to the plasma edge region. This new method is useful for overlapping signals, such as the multi-pass TS signals.

III. ANALYSIS OF MPTS SIGNALS

We have previously developed an MPTS system that uses polarization optics and an image relay system to increase the TS signal intensity.[3,16,17] The MP system controls the polarization of the laser beam with a Pockels cell (FastPulse, Q1059P12SG-1064) and a polarizer, and confines the laser beam between the two reflection mirrors. In Fig. 3(a), the MPTS signal and fitted waveform of MPTS signal are shown with the red solid line and blue dotted line, respectively. The signal intensity summed from the 1st-pass to the 10th-pass TS signal is up to about five times larger than the 1st-pass TS signal intensity. The different intervals between the pass signals result from the different distances between the reflection mirror and the plasma in the arrangement of the optics.

The interval between each MPTS signal is too short to analyze the TS signal at each pass using the raw TS signal. We then fitted the 1st-pass TS signal and subtracted its waveform from the MP signal. We repeated this procedure for the next TS pass signal and fit all the signals of each pass to analyze each TS signal intensity. The electron temperatures of the 1st-pass TS signal, TS signals from the 1st to the 6th pass, and from the 1st to the 10th pass are 23 ± 4 eV, 22 ± 2 eV, and 22 ± 3 eV, respectively. The T_e calculation using the TS signals from the 1st to the 6th pass is the most effective for decreasing the measurement error from 17% to 9%, as compared with the 1st-pass TS signal. The accuracy of the electron temperature measurement is thus improved by using MPTS. We used the new fitting method to obtain the signal intensities of each pass separately and calculated the time dependent T_e in the interval of 20 or 50 ns (Figure 3(b)), which refers to MHz sampling. The errors for the TS signals from the 7th to the 10th pass are large because of the low signal intensities. For the TS signals from the 1st to the 6th pass, the errors are about 15%. There is thus a variation in the obtained electron temperatures. However, the electron collision time is about 700 ns in this

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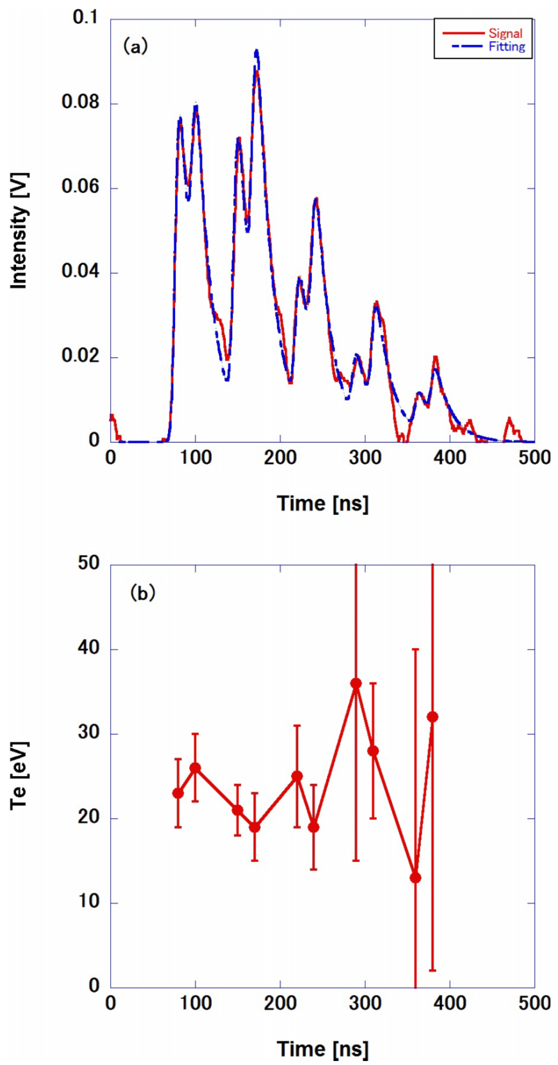

FIG. 3. (a) Fitted waveform and multi-pass TS signal. (b) Time development of the electron temperature.

plasma, and the electron temperature is almost constant during the measured 400 ns. In low temperature plasmas such as divertor plasmas, SMBI (Supersonic Molecular Beam Injection), and pellet-injected plasmas, high time resolved electron temperature measurement is important, and the MPTS system and this analysis method may be used in those cases.

We thus successfully improved the accuracy of the electron temperature measurement by using the fitting method, and we obtained high time-resolved electron temperature measurements of MPTS signals at a high repetition rate.

IV. SUMMARY

We developed an analysis method by fitting the raw TS signals for obtaining the original signal intensities in order to improve the accuracy of T_e measurements. The errors in the T_e measurements decreased at both the core and the edge region. Moreover, we applied the analysis method to MPTS signals and successfully measured the time-dependent T_e values with MHz sampling.

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